Control of Space Technology 7 Disturbance Reduction System Experiment

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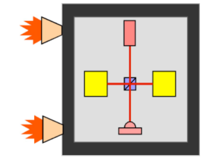
Disturbance Reduction System (DRS)



- **DRS is a collection of control systems designed to maintain the spacecraft's position with respect to free-floating test masses while maintaining coarse attitude pointing**

- **It comprises three control systems:**

  - ❑Drag-free control system (DFC) which controls the translational and rotational motion (in science band) of the spacecraft
  - ❑Attitude control system (ACS) which controls the attitude of the spacecraft
  - ❑Drag-Free sensor (DFS) control system which maintains the relative attitude and position of the test masses with respect to their housings

DRS Requirements

- **Maintain a coarse S/C attitude pointing of 2 degree: The DCS shall keep the spacecraft pointed to within 2º of a target (nominally, the Sun) in all modes.**
  - Relief at handover: 4º during the first two hours

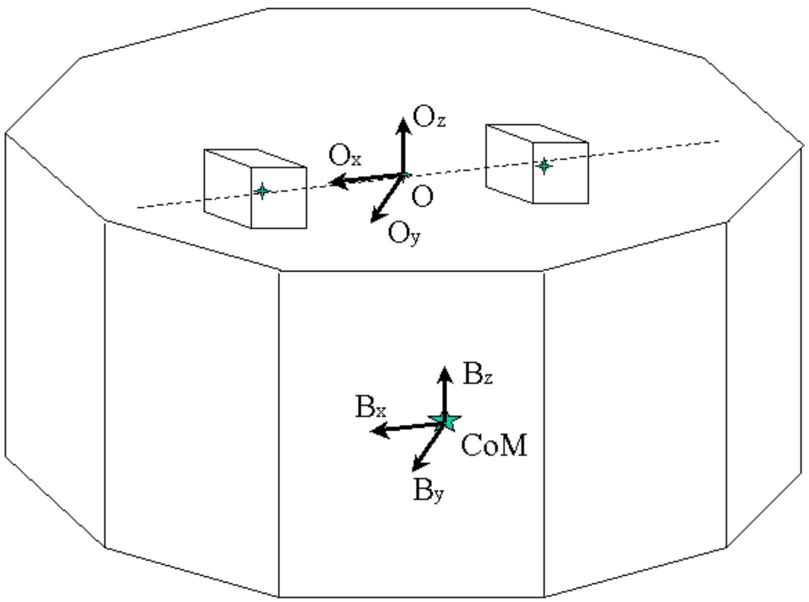
- **The DCS shall control the spacecraft position with respect to the reference test mass to better than 10 nm/√Hz over the frequency range of 1 mHz to 30 mHz, along the measurement axis.**
  - Both test masses can serve as the reference test mass

- **In its dual drag-free mode, DRS control shall strive to meet the goal of maintaining the residual accelerations along the measurement axes of both test masses to better than 30(1+f/(3 mHz)^2 fm/s^2 /√Hz in the measurement band.**
  - This remain a goal because ST7-DRS has no control over the DFS
  - Requirements on the remaining DOF are derived to meet this goal

DRS Modes

DRS Mission Mode ID	DRS Mission Mode	Reference Test Mass	DCS Control Mode	DFS TM1 Control Mode	DFS TM2 Control Mode
0	Off	1	N/A	N/A	N/A
1	Initialization	1	N/A	N/A	N/A
2	Standby	1	Standby	DFS Standby	DFS Standby
3	Attitude Control	1	Attitude Only	DFS Accelerometer	DFS Accelerometer
4	Zero-G	1	Accelerometer	DFS Accelerometer	DFS Accelerometer
5	Drag-Free/High Force	1	Initial Drag-Free	DFS Drag-Free 1	DFS Accelerometer
6	Drag-Free/Low Force	1	Initial Drag-Free	DFS Drag-Free 1	DFS Accelerometer
7	18-DOF/Transitional	1	Initial Drag-Free	DFS Drag-Free 1	DFS Suspended Drag-Free 1
8	18-DOF	1	Science	DFS Drag-Free 2	DFS Suspended Drag-Free 2
9	Colloidal Propelled	1	Standby	DFS Standby	DFS Standby

Current Design Configuration



Spacecraft Mass ~ 475Kg
Spacecraft inertia= [93.5,98.9,163.6] Kg.m^2
Test Mass = 1.96 Kg

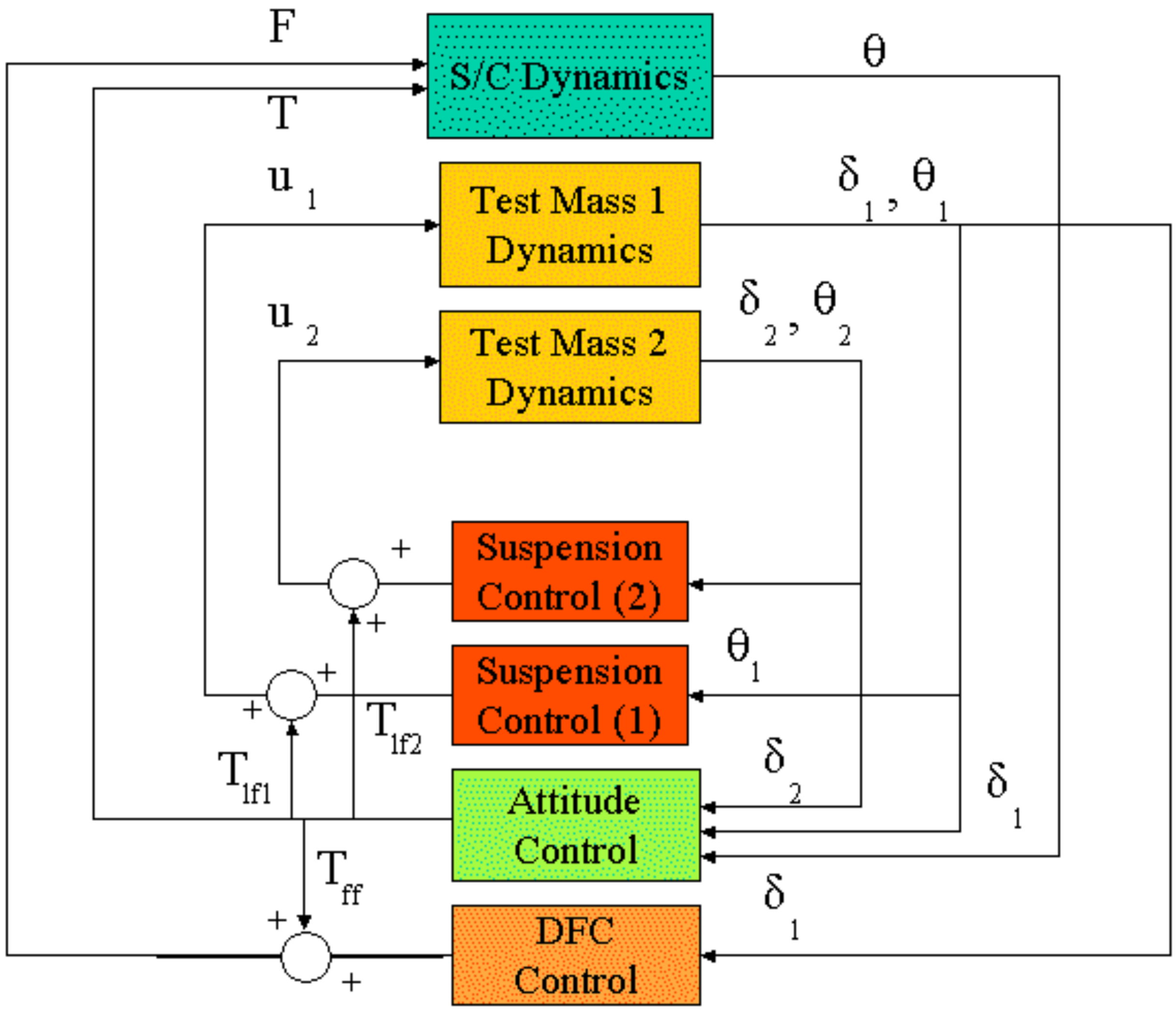
- **DCS Frame (B Frame)**
  - **Origin at the S/C center of mass**
  - **X-axis parallel to the LTP axis**
  - **Z-axis orthogonal to the Solar panel**
  - **LTP frame is parallel to the B Frame**
- **Two clusters of four colloidal micronewton thrusters @ 45 deg**
- **The LTP frame origin is ~14 cm above the center of mass**
- **The test masses are 37.6cm apart**

DRS Mode: 18-DOF

- **No suspension control of the reference test mass in translation: fully drag-free**
- **The spacecraft drag-free control ensures that the S/C follows the RTM in 4 DOFs and the NTM in 2 DOFs**
- **Low frequency (below band) suspension control of the NTM in translation: no control in the science band (1 mHz-30 mHz)**
- **Suspension control of RTM and NTM attitudes below band**
- **The spacecraft Torque control is designed to:**
  - Properly orient the spacecraft in the low frequency band using the star tracker data (2° Sun pointing)
  - Center the spacecraft about the non-reference test mass in the transverse directions in the measurement band
  - Follow the reference test mass about the roll axis (measurement axis) in the measurement band

ST7-DRS Controls

18-DOF Mode



S/C Torque Control

- **The torque controller is a 8-input/three-output controller, which uses star tracker measurements, the relative attitude of the the reference test mass about roll, and the relative position of test masses, in the y and z direction, as inputs.**

Attitude Control

Drag-Free Control

$$T(z) = K_{al}(z)\theta(z) + K_{ah}(z)\begin{Bmatrix} \theta_1 \\ y_1(z) \\ z_1(z) \\ y_2(z) \\ z_2(z) \end{Bmatrix}$$

- $K_{al}(z)$ **denotes the low-bandwidth part of the torque control designed to maintain the attitude of the spacecraft**
  - PID controllers with cross-over frequencies of ~0.03-0.06 mHz (Elliptic and Butterworth filters)

- **Feed-through compensation to the reference and non-reference test masses**

$$u_{t_{RTM}}(z) = J_{TM_X}[1 \quad 0 \quad 0] A_{SC2DFS} J_{SC}^{-1} * T_l(z)$$

$$u_{f_{NTM}}(z) = A_{SC2DFS}(\vec{p}_1 - \vec{p}_2) \times H_l * T_l(z)$$

  - This compensation removes a significant part of the coupling between the attitude control loop and the test mass suspension loops

Attitude Control (Cont'd)

- $K_{ah}(z)$ **represents the complementary attitude controller responsible for establishing:**
  - Drag-free motion of the non-reference test mass in the transverse directions in the science band
  - Drag-free motion of the roll attitude of the reference test mass in the science band
- **The relative position error of the test masses in the transverse direction are used to compute the required rotation (in DFS frame) of the DFS package about the reference test mass in y and z.**
  - The required rotation command is transformed into S/C frame and is used as input to a complementary controller to regulate the S/C attitude in the science band.
  - To obtain a pure rotation about the reference test mass, feedforward translation command are generated and issued to the drag-free controller
- **The relative attitude of the test mass about roll are used to compute the required rotation (in DFS frame) of the spacecraft**
- **This controller is also designed based on the classical approach, and is a series combination of lead-lag filter, lag filter, and an attenuation filter (Elliptic and Butterworth filters)**

Complementary Attitude Controller

Gap Measurements

$$\begin{aligned}\theta'_x &= \theta_{1x}\\ \theta'_y &= (g_{z1} - g_{z2})/\ell\\ \theta'_z &= (-g_{y1} + g_{y2})/\ell\end{aligned}$$

$$\begin{Bmatrix}\theta_x\\ \theta_y\\ \theta_z\end{Bmatrix} = A_{grs2sc}\begin{Bmatrix}\theta'_x\\ \theta'_y\\ \theta'_z\end{Bmatrix}$$

S/C Attitude Error

S/C Translational Control

- **Ensures that the spacecraft follows the RTM in 3 DOFs**
- **Translational control is a classical controller with a 4th order attenuation filter (Chebyshev & Butterworth)**
  - Lead-lag design with shaping filter
  - Uses the displacement of the reference test mass as its input
  - Cross-over @ 0.023-0.06 Hz

$$u_{DFC}(z) = K_{DFC}(z) A_{grs2sc} y(z) + \vec{p} \times [H * T(z)]$$

- **A feedforward compensation is implemented in the drag-free loop to compensate for attitude control commands as well as to reduce the coupling between the translation and attitude control loops.**
- **Controller bandwidth high enough such that test mass stiffness is not as issue in the design**

DFS Control: Drag-Free

- **Suspension control of the reference test mass attitude**
- **Classical controller with 5th order attenuation filter (Butterworth)**
  - Uses the relative attitude error of the reference test mass as its input
  - Lead/lag design with shaping filters and integral action
  - Cross-over @ ~0.56-0.57 mHz
  - Roll axis suspension control mainly below band (CACS controls within band)
- **Bandwidth limited by the cross-axes stiffness coupling**
- **CACS provide high-bandwidth drag-free control of the roll attitude within the science band : test mass stiffness is not as issue in the design**
- **Controller bandwidth high enough (in y & z) to provide enough margin: test mass stiffness consideration**

DFS Control: Suspended Drag-Free (Attitude)

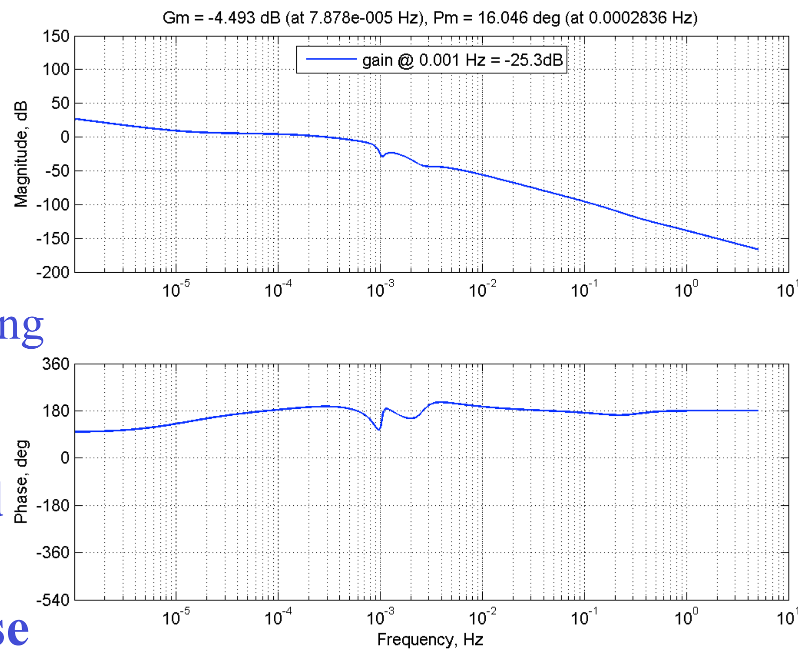
- **Suspension control of the non-reference test mass attitude**
- **Classical controller with 4th order attenuation filter (Chebyshev)**
  - Uses the relative attitude error of the non-reference test mass as its input
  - Lead/lag design with shaping filters and integral action
  - Cross-over @ ~0.51-0.57 mHz
- **Controller bandwidth high enough to provide enough margin: test mass stiffness consideration**

DFS Control: Suspended Drag-Free (Translation)

- **Suspension control of the non-reference test mass relative position**
- **Classical PID controller with 6th order attenuation filter (Chebyshev & Butterworth)**
  - Uses the relative position error of the non-reference test mass as its input
  - Lead/Lag design with shaping filters and integral action
  - Cross-over @ ~0.56 mHz
- **Below band control of the transverse motion of the test mass via suspension: low bandwidth loop**
  - CACS provides in-band control: Stiffness not an issue
- **The translation along the sensitive axis has to be solely controlled with electrostatic suspension**

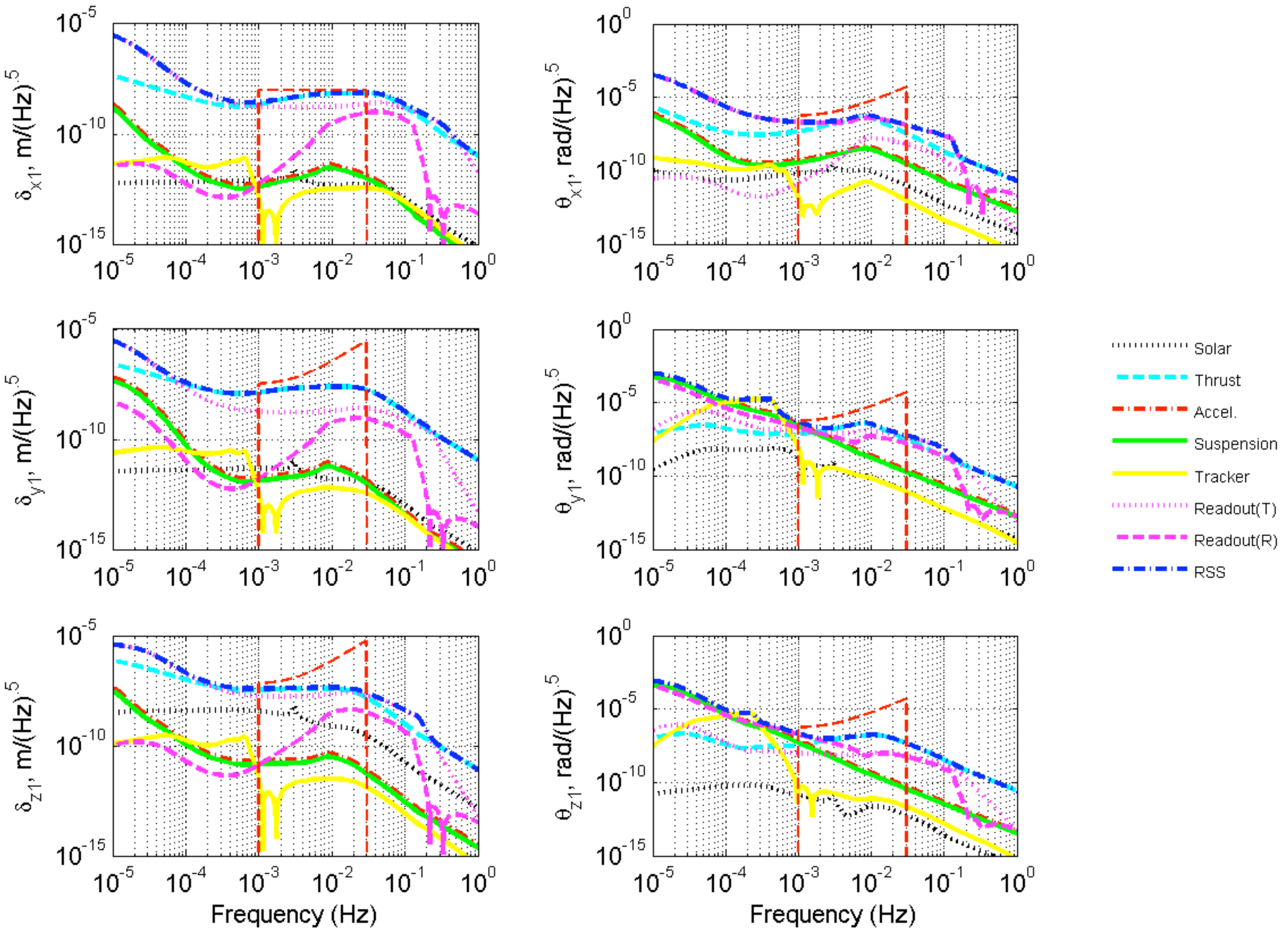
DFS Control: Suspended Drag-Free (Translation)

- **Test mass stiffness is capped at ±3.92e-6 Nm/m**
- **This potentially gives a plant with an unstable pole at 0.225 mHz**
- **The suspension controller must:**
  - Provide reasonable margin beyond stabilizing the plant
  - Attenuate before 1mHz to avoid accelerating the test mass in the science band

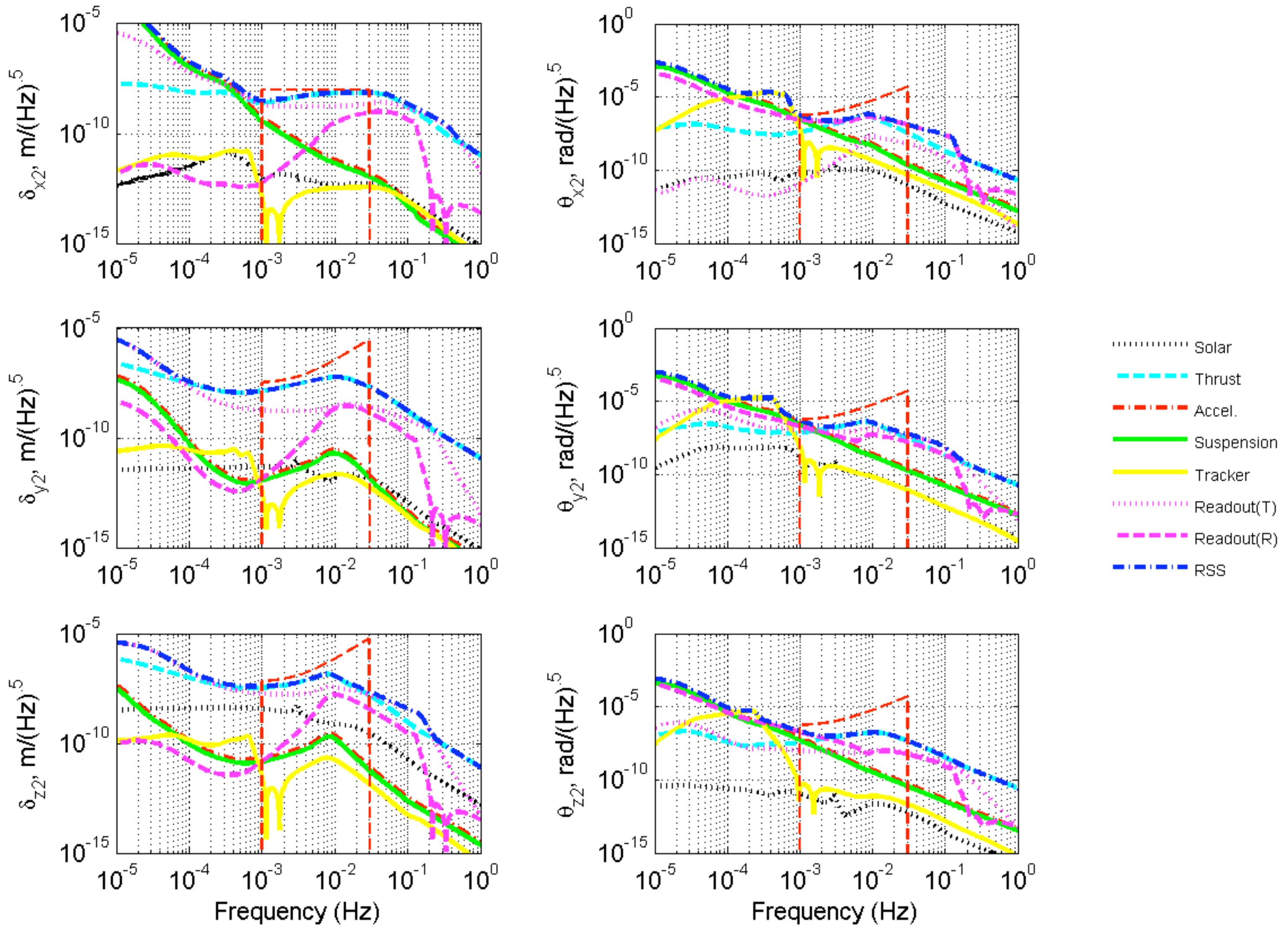


- **Result: Trade-off between margins and acceleration performance**
- **Lower PM should be acceptable because of the low-frequency cross-over**

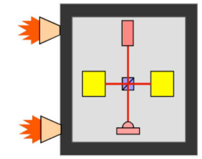
Reference Test Mass Displacements

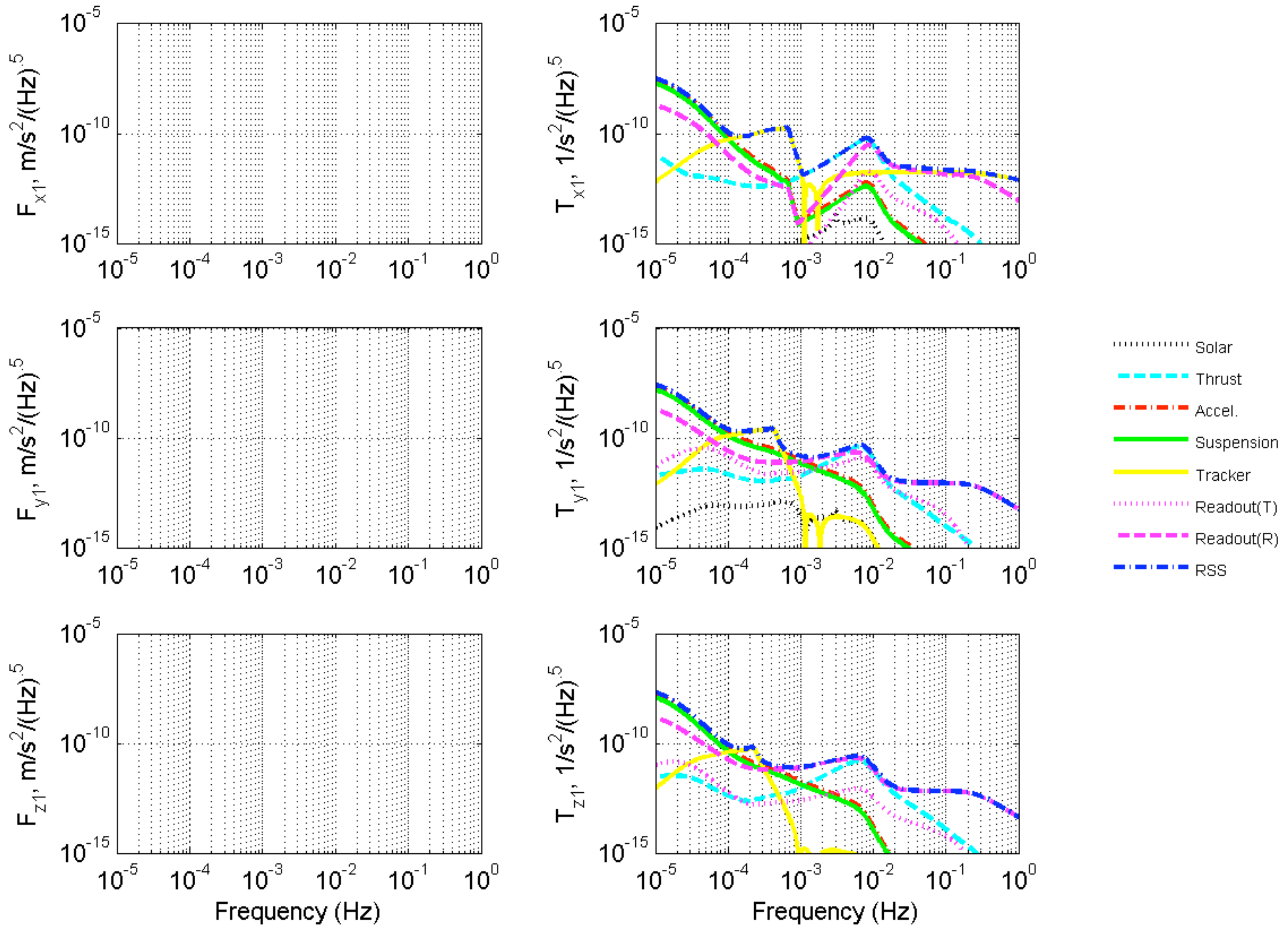


Non-Reference Test Mass Displacements

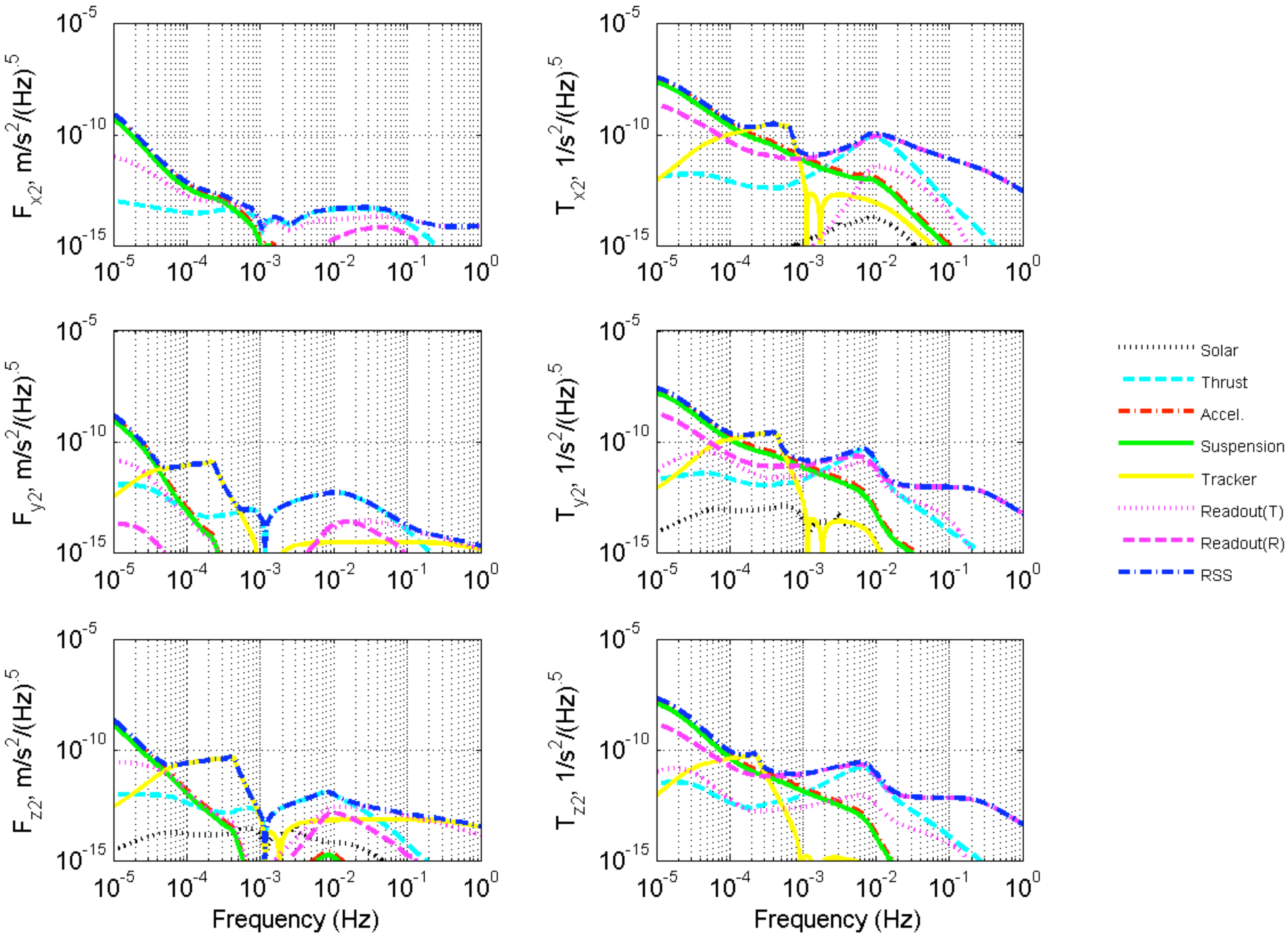


Suspension Forces and Torques: RTM





Suspension Forces and Torques: NTM



Performance

	1mHz	2mHz	3mHz	5mHz	8mHz	10mHz	20mHz	30mHz
TM1 Position, Sensitive (nm/√Hz)	**2.85**	**3.84**	**4.78**	**6.00**	**6.86**	**7.06**	**7.46**	**7.55**
TM1 Position, Trans. (nm /√Hz)	**38.5**	**40.2**	**41.6**	**42.5**	**44.6**	**44.7**	**36.7**	**24.1**
TM2 Position, Sensitive (nm /√Hz)	**2.97**	**3.91**	**4.81**	**6.01**	**6.87**	**7.07**	**7.47**	**7.55**
TM2 Position, Trans. (nm /√Hz)	**38.6**	**46.3**	**57.7**	**92.0**	**146.9**	**115.5**	**39.3**	**21.9**
TM1 attitude (nrad /√Hz)	**484.3**	**206.0**	**233.1**	**342.9**	**615.4**	**545.5**	**222.3**	**126.0**
TM2 attitude (nrad /√Hz)	**562.6**	**250.3**	**243.9**	**342.6**	**653.0**	**579.5**	**224.6**	**126.2**
TM1 residual acceleration, Suspension X-talk (fm/s^2 /√Hz)	**3.90**	**4.57**	**6.54**	**11.92**	**17.05**	**9.58**	**0.91**	**0.73**
TM2 residual acceleration, Suspension X-talk (fm/s^2 /√Hz)	**9.35**	**15.07**	**14.14**	**32.33**	**49.01**	**51.67**	**51.30**	**51.08**
TM1 residual acceleration, Stiffness (fm/s^2 /√Hz)	**5.79**	**7.73**	**9.61**	**12.02**	**13.78**	**14.18**	**14.96**	**15.10**
TM2 residual acceleration, Stiffness (fm/s^2 /√Hz)	**6.06**	**7.89**	**9.71**	**12.20**	**14.12**	**14.40**	**14.98**	**15.11**

Acceleration Performance: RTM

	1mHz	2mHz	3mHz	5mHz	8mHz	10mHz	20mHz	30mHz
TM1 residual acceleration, Suspension X-talk (fm/s^2)	**3.90**	**4.57**	**6.54**	**11.92**	**17.05**	**9.58**	**0.91**	**0.73**
TM1 residual acceleration, Stiffness (fm/s^2)	**5.79**	**7.73**	**9.61**	**12.02**	**13.78**	**14.18**	**14.96**	**15.10**
Internal Forces (fm/s^2)	**27.78**	**36.11**	**50.00**	**94.44**	**202.78**	**302.78**	**1136.1**	**25003**
Total RSS (fm/s^2)	**28.64**	**37.21**	**51.33**	**95.95**	**203.96**	**303.26**	**1136.2**	**25003**
Requirements (fm/s^2)	**33.33**	**43.33**	**60.00**	**113.33**	**243.33**	**363.33**	**1363.3**	**30003**

Acceleration Performance: NTM

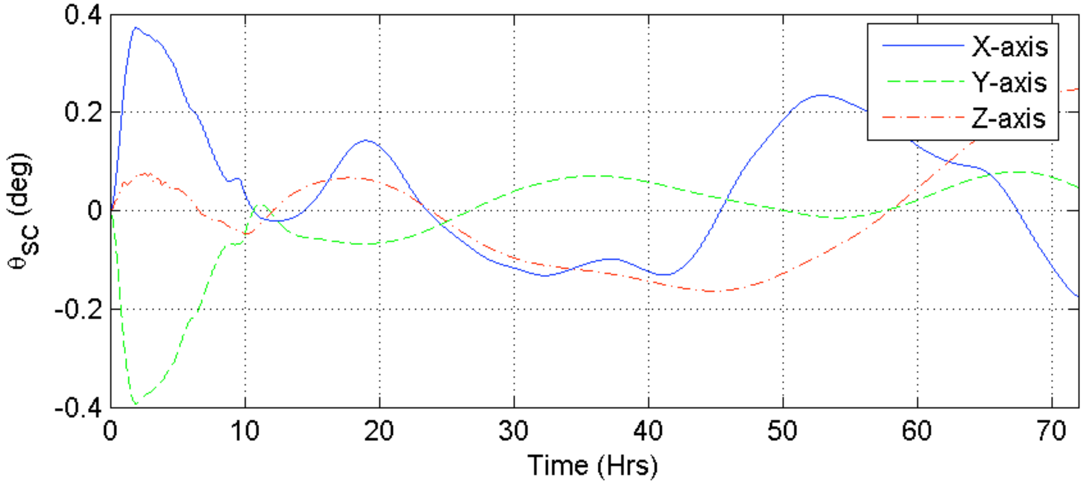
	1mHz	2mHz	3mHz	5mHz	8mHz	10mHz	20mHz	30mHz
TM2 residual acceleration, Suspension X-talk (fm/s^2)	9.35	15.07	14.14	32.33	49.01	51.67	51.30	51.08
TM2 residual acceleration, Stiffness (fm/s^2)	6.06	7.89	9.71	12.20	14.12	14.40	14.98	15.11
Internal Forces (fm/s^2)	27.78	36.11	50.00	94.44	202.78	302.78	1136.1	25003
Total RSS (fm/s^2)	29.93	39.92	52.86	100.56	209.10	307.50	1137.4	25003
Requirements (fm/s^2)	33.33	43.33	60.00	113.33	243.33	363.33	1363.3	30003

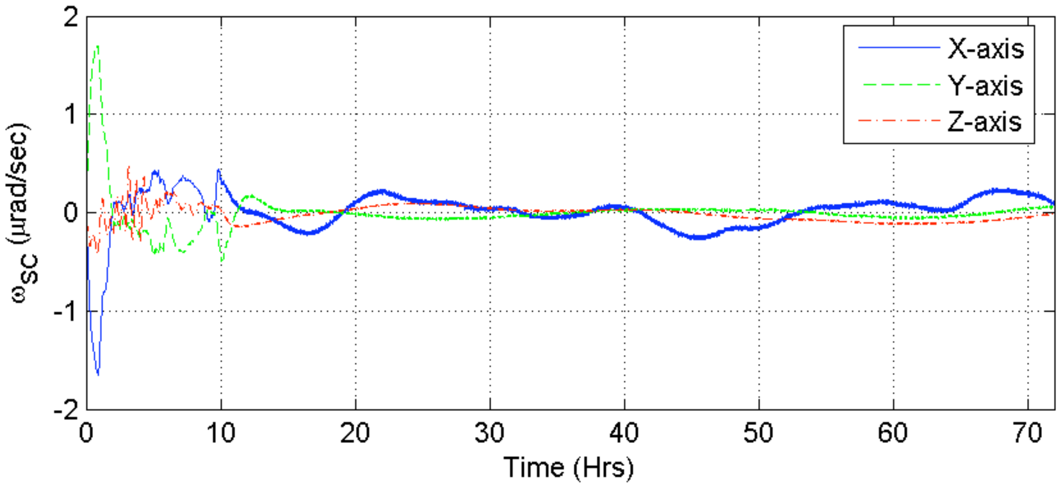
Mode Transitions: Approach

➢DCS and DFS controls use direct switch-over

- DC forces cause large transients because of the soft control loops
- Mean filters are used to compute a running average of the control thrusts
- Mean filters also considered for the suspension commands.
- The output of the mean filter is latched at each transition: the latched values include the DC-related control forces and torques
- The latched mean values are added as a bias to the control inputs at each transition

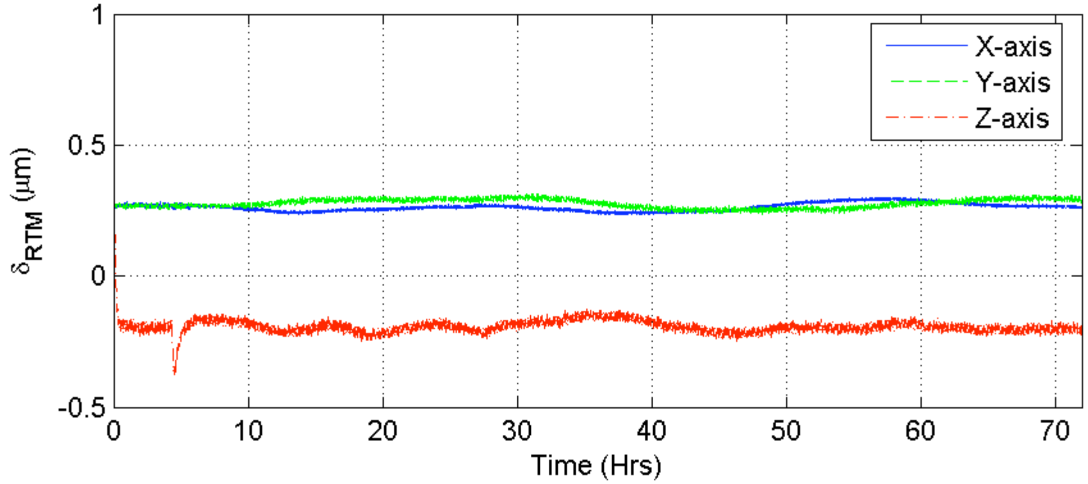
Mode Transition: S/C Attitude

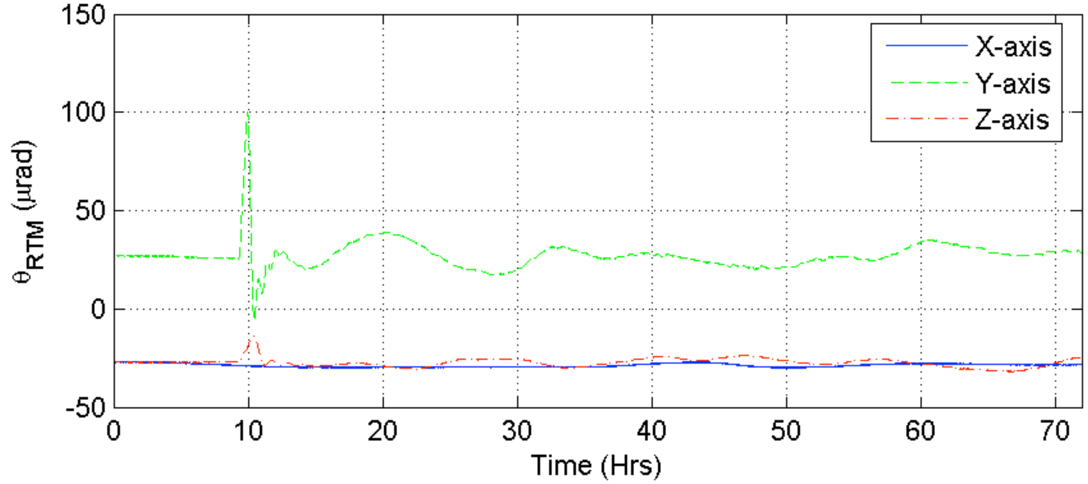




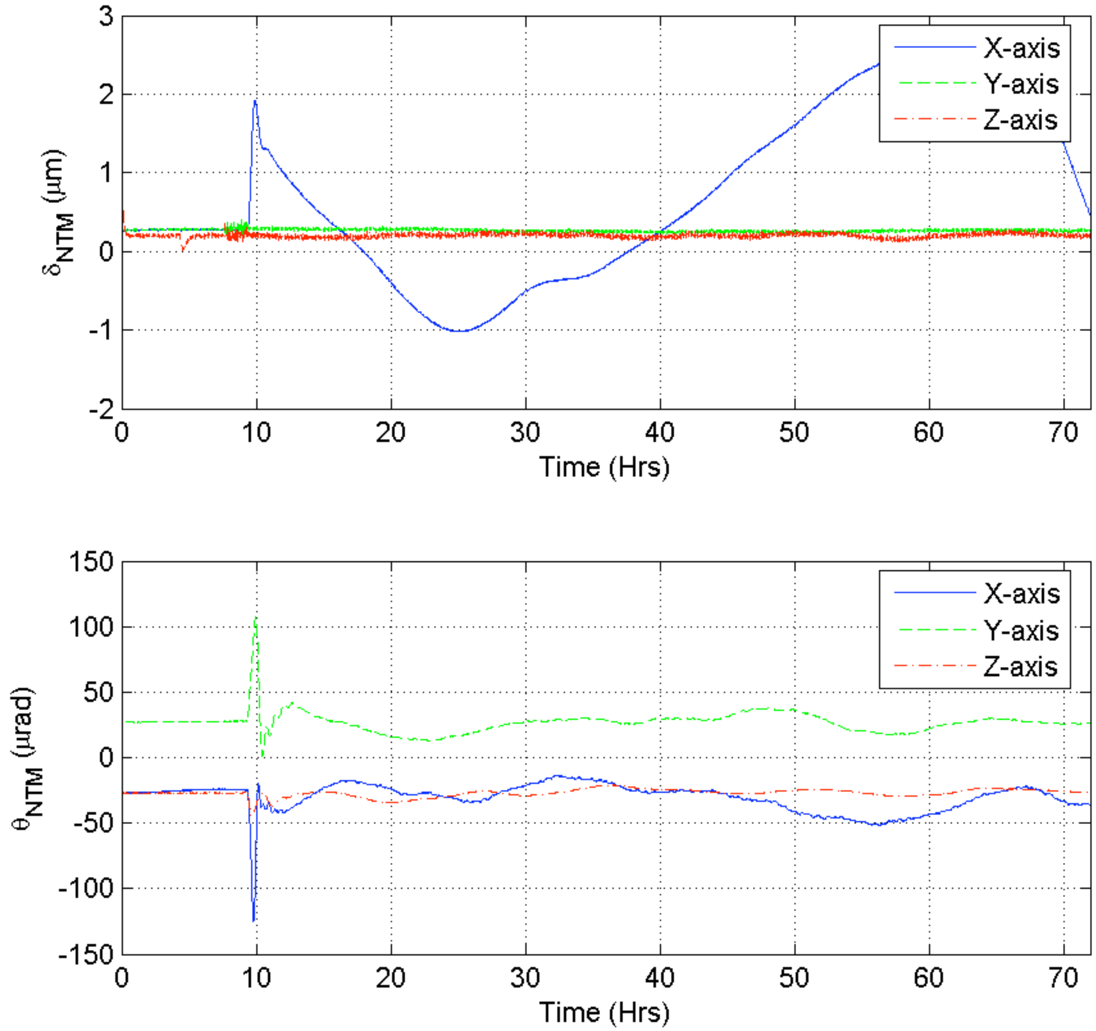
ST7-DRS Controls

Mode Transition: RTM Gaps





Mode Transition: NTM Gaps



Summary

- **Control Designs for all modes of the ST7/DRS have been completed.**
  - Spacecraft controls (DCS)
  - Drag-Free Sensor Controls (DFS)

- **Feasibility of each of the modes has been demonstrated.**

- **Performance and stability predictions have been verified via the high fidelity simulation**

- **A Mode transition scheme based on direct transition with latched mean thrust levels has been implemented and verified.**